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Hole Drift Mobilities in CIGS Solar Cells

We continued our work on drift-mobility measurements in CIGS. As noted in previous reports, our hole drift-mobilities in CIGS are about 0.1 cm^2/Vs, which is about 30-100 times lower than estimated using admittance measurements by Dave Cohen's group at Oregon. The distinction is very important for understanding solar cells; low-mobility solar cells are understood very differently than are high-mobility cells, and 1 cm^2/Vs is about the dividing line between the two types of behavior.

In this quarter we have begun to address this apparent discrepancy between the two groups' measurements. If we assume that both our measurements and those of Cohen's group are sound, then there are two physical differences that need to be considered as mechanisms for the difference. The first is a true difference between the samples; Cohen's group has worked primarily with samples from the Institute for Energy Conversion (IEC) at University of Delaware, and we have worked with samples from Noufi's group at NREL. The second is vertical inhomogeneity. There are two distinct physical regions in CIGS cells: a top region, extending about 0.5 micron below the CdS/TCO layers, that accounts for most external potential drops across the cells, and a thicker, conductive bottom region. The admittance method for mobility measurements is mainly sensitive to the bottom region; our method is sensitive to the top region. So it is conceivable that there is a significant difference in mobilities between the top and bottom regions, with the top region having the smaller mobility.

We therefore requested that IEC send us some samples comparable to those that Cohen's group worked with for our use with drift-mobility measurements; Bill Shafarman has been our contact at IEC. These samples were recently received, and we expect to have results for time-of-flight drift mobilities shortly.

V_{OC} in Nanocrystalline Silicon Solar Cells

An important distinction between amorphous silicon solar cells and nanocrystalline silicon solar cells is that the difference E_{gap}-eV_{OC} between the bandgap E_{gap} and the open-circuit "energy" eV_{OC} is substantially smaller for the nanocrystalline cells. Roughly speaking, E_{gap}-eV_{OC} is about 0.8 eV for a-Si:H, and about 0.5-0.6 eV for nc-Si:H.

We realized that the hole drift-mobility measurements we published last year (T. Dylla, F. Finger, and E. A. Schiff, *Appl. Phys. Lett.* **87**, 032103 (2005). DOI:10.1063/1.1984087. [.pdfT]) provide a fairly satisfactory explanation for this difference. The remarkable aspect of the hole drift-mobility measurement in nc-Si:H was that the hole drift has amorphous-like, valence bandtail limited behavior, but the "attempt-frequency" parameter was much lower for nc-Si:H than for a-Si:H (about 2-3 orders of magnitude). This difference can be plausibly explained if the bandedge density-of-states N_V is lower by a corresponding degree in nc-Si:H.

Using the same "bandtail-limited" model for a-Si:H and for nc-Si:H, but in each case employing the parameters obtained from the very different hole drift-mobilities in the 2 materials, accounts well for the best values E_{gap}-eV_{OC} in each material; of course it is possible to prepare samples with poorer values, by using preparation conditions that (i) yield large initial defect densities, (ii) yield poorer hole drift mobility than assumed, (iii) have poor interfaces or doped layers, etc..

In the figure below we show the thickness-dependent fill-factors and V_{OC} values for nc-Si:H using these parameters. We also show a number of published values for individual cells prepared at Forschungszentrum Juelich and at United Solar. A very good cell from Juelich (9.8% efficiency) has a fill-factor that is essentially the same as predicted by the hole-mobility based model, which seems sensible given that the hole mobility

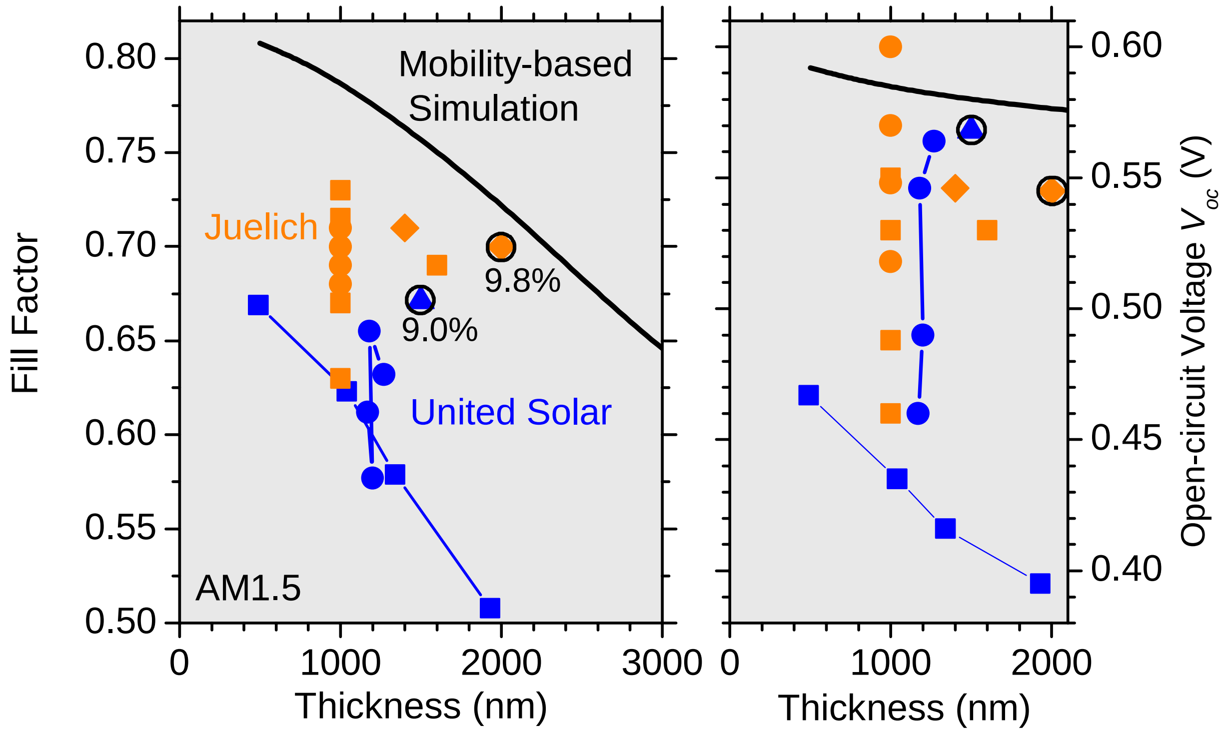

Figure illustrates fill-factors and open-circuit voltages vs. thickness for nanocrystalline silicon solar cells from Forschungszentrum Juelich and from United Solar. One high-efficiency cell from each group is indicated. The solid black line is the hole mobility (valence bandtail) limit based on parameters taken from hole drift-mobility measurements.

parameters were obtained from a Juelich sample. The best cell (9.0%) from United Solar has a fill-factor noticeably below the hole-mobility calculation. One might speculate that the lower fill-factors correspond to a poorer hole mobilities than for the Juelich material; unfortunately, hole drift mobility measurements haven't been done on United Solar samples.

Metastability and V_{OC} in a-Si:H Solar Cells

We have been exploring the reasons for the fact that the saturation of the Staebler-Wronski effect generally occurs when the degradation of the optoelectronic properties has just become significant – *under solar illumination*. The small decline of the open-circuit voltage in working a-Si:H solar cells under illumination is the best indicator of what we term "self-limiting" behavior.

Presuming that defect creation is responsible for this degradation, self-limitation implies that the saturation defect density N_{sat} is comparable to the "crossover density" $N_{crossover}$, where the latter is the defect density for which half of photocarrier recombination occurs at defect sites, and half at bandtail sites.

We find that the equation $N_{sat} \approx N_{crossover}$ provides a good account for intensity-dependence of N_{sat} (as reported by other groups). However, this relation predicts that N_{sat} should be smaller at elevated temperatures than has been reported; T-dependence of N_{sat} is fairly small.

Based on this analysis, we now recommend studying the kinetics of V_{OC} during degradation at elevated temperatures, where the defect density would apparently rise well beyond the crossover density and V_{OC} degradation should become more evident. We would expect this to clarify the saturation mechanism, but it doesn't seem likely that we'll be able to do this under the present subcontract.